Rare Kaon Decays

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Abstract. Rare kaon decays via Flavor Changing Neutral Currents are discussed in the context of the CKM unitarity triangle with a particular interest in the rare kaon decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$. New results and the status of these experiments are reported.

INTRODUCTION

The study of rare kaon decays has a glorious history. At the level of 10^{-1} in branching ratio, parity violation was first "discovered" as the θ-τ puzzle [1], CP violation was discovered at the level of 10^{-3} [2], and the GIM mechanism [3] was suggested by the strong suppression of the decay $K_L^0 \to \mu^+\mu^-$, or the absence of the Flavor Changing Neutral Currents (FCNC)— the decay mode was subsequently found at the level of 10^{-8}. Further searches for rare kaon decays at lower branching ratio undoubtably involve rich physics and may yet offer another surprise— e.g. they are likely to elucidate the origin of CP violation, and provide some clues for physics beyond the Standard Model (SM). In this talk, the decay modes via FCNC with the expected branching ratios of less than 10^{-9} are discussed. Since exotic decays violating the lepton flavor conservation law have been discussed by the previous speaker [4], the focus of this talk is on the rare kaon decays which are allowed in the SM.

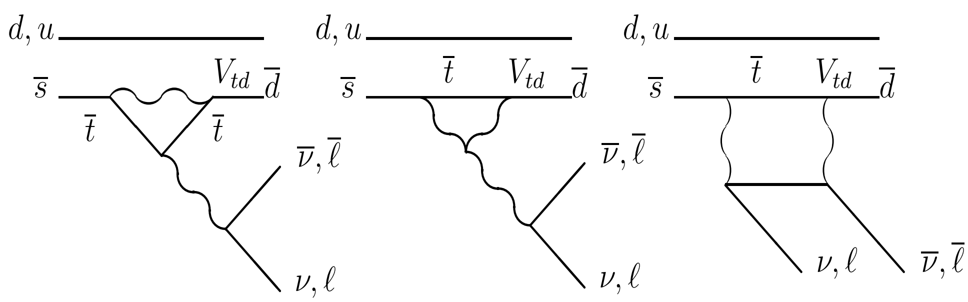

FIGURE 1. Typical Feynman diagrams.

Typical leading Feynman diagrams of these decays are shown in Fig. 1, where d and u at the top lines are for K^0 and K^+ decays, respectively, and ℓ indicates the electron or the muon. Because of the GIM mechanism, the lowest order diagrams come from second order weak interactions with a u-type quark in the loop diagrams, in which the top-quark contributions dominate because of the mass. This makes these decay modes very sensitive to V_{td}, the least constrained coupling-constant of the top and down quarks in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Due to one of the unitarity conditions of the CKM matrix $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ and with the approximation $V_{ud} \sim V_{tb} \sim 1$, V_{td} and V_{ub}^* form two sides of a unitarity triangle as shown in Fig. 2. The height of the triangle $Im(V_{td})$ is an indication of "direct" CP violation, or CP violation through the decay amplitude. For the decay $K^+ \to \pi^+\nu\bar{\nu}$, the branching ratio is roughly proportional to $|V_{td}|^2$ and for $K_L^0 \to \pi^0\nu\bar{\nu}$ to $Im^2(V_{td})$. These measurements alone can determine the unitarity triangle, and when they are combined with measurements from B-decays it will provide over-constrained information that is sensitive to a presence of supersymmetry and other physics beyond the SM [5,6].

DECAYS $K_L^0 \to \pi^0\ell^+\ell^-$ AND $K_L^0 \to \ell^+\ell^-$

If the final states include a charged lepton pair, there are additional contributions from diagrams with virtual photons that usually prevent clear interpretations of measurements [7].

The decays $K_L^0 \to \pi^0\ell^+\ell^-$ have a "direct" CP violating component, which is expected to occur, if it were the only component, at a branching ratio of $\sim 5 \times 10^{-12}$. There are two other contributions, however, at the same level to this process; one arises from the mixing of the CP even state in K_L^0, and the other from two-virtual-photon intermediate states that conserve CP. At present, there are theoretical am-

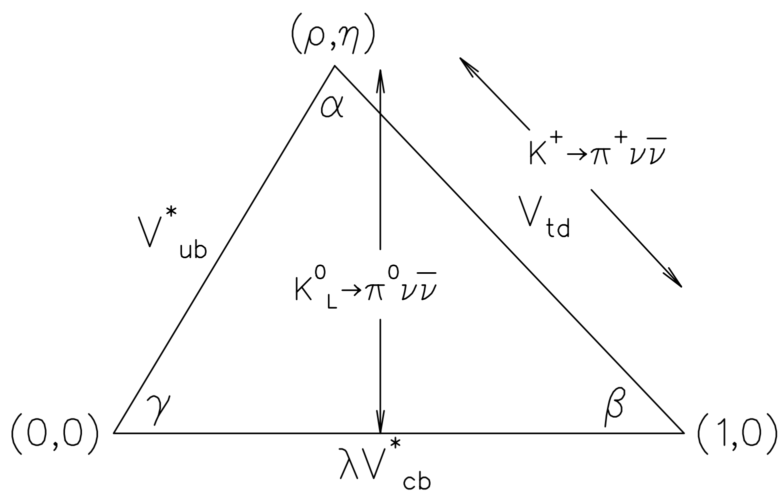

FIGURE 2. Unitarity triangle. The coordinates of the vertices are for the rescaled triangle[8].

biguities in the estimations of these contributions, which may eventually be sorted out by measurements of $K_S^0 \to \pi^0 \ell^+ \ell^-$ and other radiative decays. To make the matter a bit more complicated, there is a physical background coming from the radiative decay $K_L^0 \to \ell^+ \ell^- \gamma\gamma$, which has the identical event topology. With the tightest cuts, the background level is estimated to be still at a 10^{-11} level for $\ell = e$ [9]. The situation is similar in the case of $\ell = \mu$. The present upper limits (90 % c.l.) are $B(K_L^0 \to \pi^0 e^+ e^-) \leq 5.6 \times 10^{-10}$ [10] and $B(K_L^0 \to \pi^0 \mu^+ \mu^-) \leq 3.8 \times 10^{-10}$ [11].

The decay $K_L^0 \to e^+ e^-$ is very similar to $K_L^0 \to \mu^+ \mu^-$, which is sensitive to the ρ parameter [8], but it is further suppressed by the helicity mechanism. This decay is sensitive to pseudo-scalar interactions coming from physics beyond the SM. Four events from the decay $K_L^0 \to e^+ e^-$ have been reported recently which correspond to a branching ratio, $B(K_L^0 \to e^- e^+) = 8.7^{+5.7}_{-4.1} \times 10^{-12}$ [12], being consistent with the unitarity bound expected from the long-distance contributions.

DECAY $K^+ \to \pi^+ \nu\bar{\nu}$

In the SM calculation of the decay $K^+ \to \pi^+ \nu\bar{\nu}$, the dominant contribution comes from second order loop diagrams with a virtual top quark (Fig. 1). The hadronic matrix element can be extracted from the decay $K \to \pi^0 e^+ \nu$ and theoretical uncertainties in the calculation due to long distance contributions and other effects are small [5]. The signature of the decay $K^+ \to \pi^+ \nu\bar{\nu}$ is a single pion with no other observable decay-products. Definitive observation of this signal requires that all possible backgrounds are suppressed well below the signal level. Major background sources are: a muon from the copious decay $K^+ \to \mu^+ \nu$ ($K_{\mu 2}$) which is misidentified as a pion, a pion from the decay $K^+ \to \pi^+ \pi^0$ ($K_{\pi 2}$) when two photons from the π^0 decay are unobserved, a beam pion scattered by the target into the detector, and charge exchange reactions of K^+'s which result in decays $K_L^0 \to \pi^+ \ell^- \bar{\nu}$, where ℓ (e or μ) is undetected. In order to suppress the backgrounds, good particle identification, efficient photon veto, and detection of incoming particles are essential.

The E787 experiment at Brookhaven National Laboratory (BNL) as shown in Fig. 3 is designed to effectively distinguish these backgrounds from the signal. Kaons of about 700 MeV/c at a rate of $(4-7) \times 10^6$ per 1.6-s spill are detected and identified by a Čerenkov counter and hodoscopes, degraded by BeO and stopped in an active target, primarily consisting of 413 5-mm square scintillating fibers. The momentum (P), kinetic energy (E) and range (R) of decay products are measured using the target, a central drift chamber, 21 layers of 1.9-cm thick plastic scintillator (Range Stack) and two layers of straw chambers, all contained in a 1-T magnetic field. The $\pi^+ \to \mu^+ \to e^+$ decay sequence of the decay products in the Range Stack scintillator is observed by 500-MHz transient digitizers for particle identification. Photons are detected by a 4π-sr calorimeter consisting of a 14-radiation-length-

thick lead/scintillator barrel detector, 13.4-radiation-length-thick end caps of CsI crystals, and a 3.5-radiation-length-thick lead-glass Čerenkov counter which also works as an active beam degrader.

The E787 experiment reported an observation of one clean event at a branching ratio $B(K^+ \to \pi^+\nu\bar{\nu}) = 4.2^{+9.7}_{-3.5} \times 10^{-10}$ using the data sample taken in 1995 [13]. Since then, additional data samples taken in 1996 and 1997, together with those taken in 1995, have been analyzed with improved algorithms, which have resulted in less non-Gaussian tails in P, R and E measurements, and a $\sim$30 % higher acceptance than that in Ref. [13]. Also, in the 1996–7 runs, lowering the incident K^+ beam momentum resulted in a larger fraction of kaons stopping in the target, which reduced accidental hits originated from nuclear reactions in the beam degrader. The higher proton intensity at the production target compensated the kaon yield loss at lower momentum.

In order to avoid a possible bias in the analysis, the signal region is kept untouched until the background estimations as well as optimization of acceptance have been done. In the background study, the data sample after applying all the final cuts except two orthogonal (uncorrelated) cut groups to be studied, e.g. the kinematical cuts and those related to the observation of the decay sequence $\pi^+ \to \mu^+ \to e^+$ in the stopping counter for the estimation of the $K^+ \to \mu^+\nu$ background, is used to obtain the suppression factor for each cut group. The correlation between the two cut groups, which may invalidate the method, is studied by varying the cuts being studied or by enhancing certain types of background events.

The total background for the entire 1995–1997 exposure with the final analysis cuts is estimated to be 0.08 ± 0.02 events. The acceptance for $K^+ \to \pi^+\nu\bar{\nu}$, $A = 0.0021 \pm 0.0001(stat) \pm 0.0002(syst)$ is calculated based on data and Monte Carlo calculations. The largest uncertainty comes from the uncertainty in pion-nucleus interaction. The measurement of the branching ratio for $K^+ \to \pi^+\pi^0$

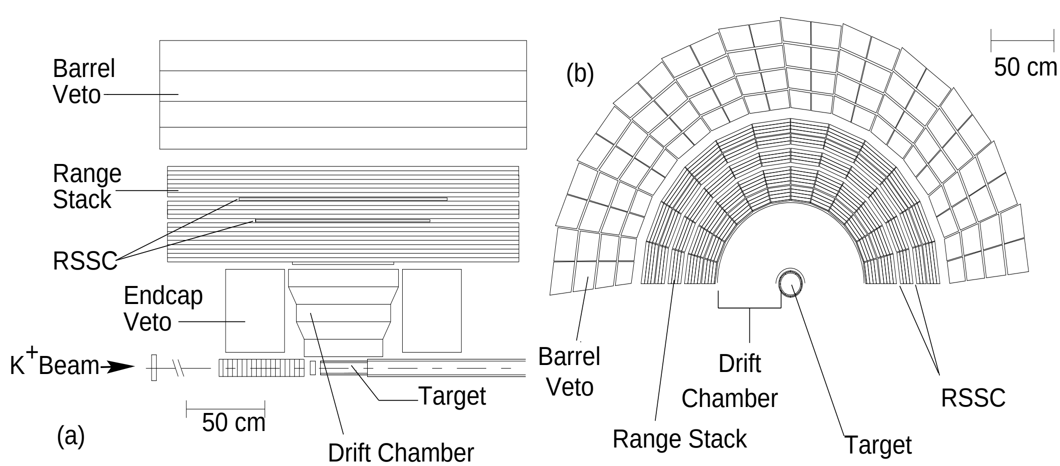

FIGURE 3. Upper half of the BNL E787/949 detector: (a) side view and (b) end view.

within a few % of Ref. [14] confirms the acceptance calculation. Analysis of the full data sample as shown in Fig. 4 has yielded only the single event previously reported. Based on the acceptance A and the total exposure of $N_{K^+} = 3.2 \times 10^{12}$ kaons, the new branching ratio is $B(K^+ \to \pi^+ \nu\bar{\nu}) = 1.5^{+3.4}_{-1.2} \times 10^{-10}$ [15]. This provides a constraint, $0.002 < |V_{td}| < 0.04$.

The goal of a new experiment E949 at BNL is to improve the sensitivity by an order of magnitude. Since the AGS in the RHIC era will be used for two hours a day to feed heavy ions into the RHIC ring, the rest of 22 hours can be used for the high energy program. The operation is expected to provide a more stable and longer running period. Exploiting a higher beam intensity, the incident K^+ momentum can be further lowered to reduce accidental coincidence. The photon veto capability will be improved by additional lead/scintillator layers in the barrel region and by additional active degrader in the beam region. In the region below the $K^+ \to \pi^+\pi^0$ peak at 205 MeV/c, where nuclear interactions result in a large momentum-tail, the additional photon veto capability may suppress the background by more than an order of magnitude as low as to the signal level, doubling the phase space in the search.

Decay $K_L^0 \to \pi^0 \nu\bar{\nu}$

The decay $K_L^0 \to \pi^0\nu\bar{\nu}$ violates the CP conservation law through decay amplitude. This process is expected to occur at $B(K_L^0 \to \pi^0\nu\bar{\nu}) \sim 3 \times 10^{-11}$ [5]. The contribution from CP mixing in K_L^0 is expected to be around 10^{-15} [16]. Since no

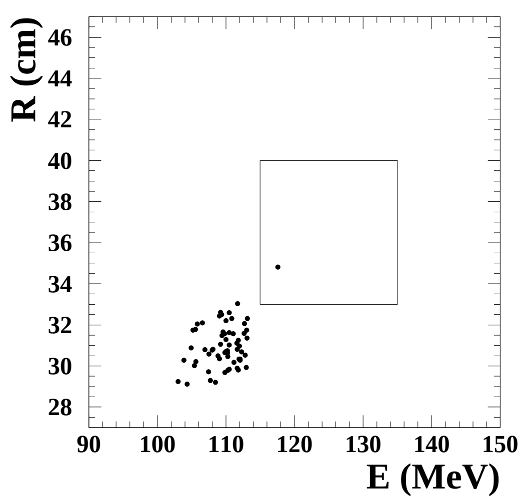

FIGURE 4. Range (cm in plastic scintillator) vs Kinetic energy plot of the 95–97 data. The concentration at E=107 MeV is due to $K_{\pi 2}$ events.

charged leptons are involved in this decay, the process is free from virtual photon contributions and clean for the study of the origin of CP violation. The theoretical ambiguity is only ~ 1 % except those in the CKM matrix elements. Conversely, the observation of this decay mode uniquely determines $Im(V_{td})$ or η in the Wolfenstein parametrization. The goal of the experiment is to determine $Im(V_{td})$ with a 10–15 % accuracy, which corresponds to a single event sensitivity of 10^{-12}. The present upper limit of this decay is 5.7×10^{-7} [17].

The decay $K_L^0 \to \pi^0 \nu \bar{\nu}$ is a three-body decay that involves only neutral particles. The signature of this decay is two photons from the π^0 and no other activity in the detector. In this decay mode, available kinematical parameters are very limited; relatively easy ones to measure are the positions and energies of γ-rays. Also, the direction and position of the K_L^0 beam can be limited by tightly collimating the beam at a cost of beam intensity. The decay vertex can be reconstructed from these two constraints with the assumption of the pion mass. The KEK experiment [18] and the FNAL approach [19] are classified in this category.

The BNL experiment E926 [20] attempts to measure more kinematic values; the directions of γ-rays and the momentum of the K_L^0. Measurements of γ-ray directions allow full reconstruction of the π^0 kinematics without the assumption of the π^0 mass, providing more constraints with redundancy, which is necessary to suppress the background to the level well below the signal. The time-of-flight (TOF) of a K_L^0 between the production target and the decay vertex can be measured for low momentum K_L^0's if the incident proton beam is bunched. This measurement allows calculation of the missing mass and kinematical reconstruction in the center of mass system, which is effective to eliminate backgrounds from two-body decays. The major decay modes of K_L^0 are $K_L^0 \to \pi^0 \pi \pi$ and $K_L^0 \to \pi^{\pm} \ell^{\mp} \nu$. Suppression of most backgrounds is achieved by high-efficiency hermetic photon and charged-particle detector system surrounding the decay volume, and kinematical constraints.

In the BNL E926 experiment, a low energy K_L^0 beam with an average momentum around 650 MeV/c is produced by irradiating a target with a 24-GeV proton beam from the AGS and extracted at 40^o with respect to the incident beam. The proton beam is bunched to form a $\leq$200 ps wide bucket at a rate of 25 MHz. About 16 % of K_L^0's decay in the 4-m long decay volume, which is evacuated to a level of 10^{-7} Torr to suppress the background from neutron-induced π^0 production. The decay region is surrounded by a charged particle veto system and a photon veto system of 18-radiation-length-thick lead/scintillator sandwiches in the barrel region. The two photons from the π^0 decay are converted into pairs of a positron and an electron in a 2-radiation-length preradiator next to the vacuum region for the measurement of the directions of the γ-rays. The preradiator consists of sandwiches of 2-mm thick scintillator, a copper plate as a mechanical support and radiator, and a tracking chamber. This is followed by an 18-radiation-length calorimeter for the measurement of γ-ray energies and for vetoing additional photons.

The estimates of sensitivity for $K_L^0 \to \pi^0 \nu \bar{\nu}$ are tightly coupled to the cuts required for background suppression, particularly for the $K_L^0 \to \pi^0 \pi^0$ and $K_L^0 \to \pi^0 \pi^+ \pi^-$ backgrounds. An acceptance of ~ 0.015 % for the case S/N=0.5 comes from

the combination of factors; 0.58 for the fiducial region and usable kaon momentum region, 0.33 for the solid angle, 0.5 for the efficiency of the preradiator, and the remaining factor for the π^0 mass cut and other cuts. Assuming three years of running with 6×10^6 kaons per 2-s beam spill (50 % duty factor), the expected number of events is 65.

The toughest background is the CP violating $K_L^0 \to \pi^0\pi^0$ decay when two photons are undetected. Backgrounds from $K_L^0 \to \pi^0\pi^0$ arise when two photons are detected in the forward detector and the other two are undetected anywhere. These backgrounds can be classified into two categories; even pairing when two photons come from the same π^0, and odd pairing when two photons come from different π^0's. Events in the even pairing category form a two-body-decay peak in the momentum spectrum of π^0 in the CM system, while the two γ-rays in the odd pairing category do not reproduce the π^0 mass. The above requirements and photon veto essentially suppress $K_L^0 \to \pi^0\pi^0$ backgrounds to 0.2 of the signal level. Similarly, $K_L^0 \to \pi^0\pi^+\pi^-$ backgrounds can be suppressed to 0.1 of the expected signal. Backgrounds from other K_L^0 decay modes are estimated to be less than 0.1 of the signal. Because of the large angle extraction, the cross sections for producing Λ's are small and they completely decay before reaching the decay volume. Backgrounds could arise from Λ's produced by halo neutrons and K_L^0's, but they are estimated to be negligible. Neutrons with $P_n \geq 800$ MeV/c can react on the remaining atoms in the vacuum region to produce π^0's. This background level is again estimated to be 0.01. Accidental backgrounds are caused by beam halo neutrons and γ-rays which create a π^0 signal in the preradiator. The background level is estimated to be 0.02 of the expected signal.

The BNL E926 was proposed in 1997 but the group is still waiting for full funding. In the present scenario, the detector construction is expected to start in 2002. The

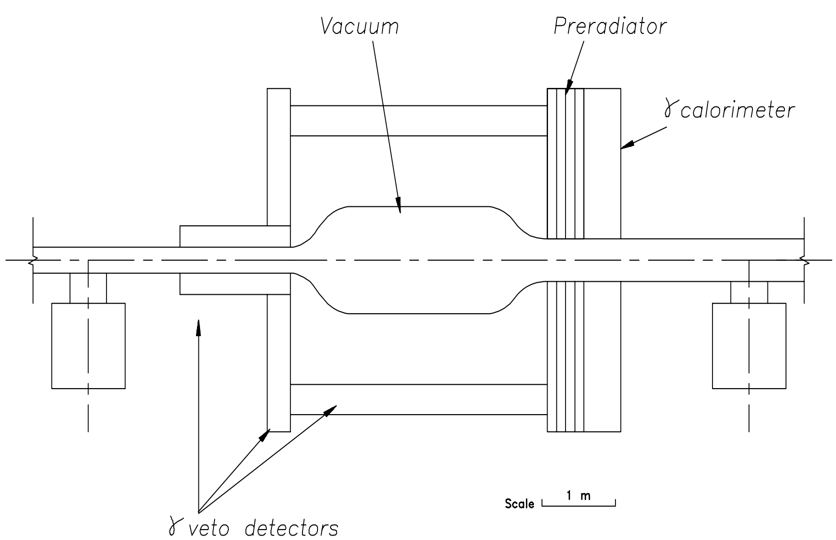

FIGURE 5. A typical detector system for $K_L^0 \to \pi^0\nu\bar{\nu}$ experiments.

KEK experiment has partially been approved, but the sensitivity goal is only around the SM level—the new Japan Hadron Facility is expected to improve the sensitivity.

CONCLUSION

Studies of rare kaon decays have contributed to the discoveries of several symmetry violations. The decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L^0 \to \pi^0 \nu\bar{\nu}$ are expected to "complete" the measurement of the CKM matrix in the next decade independently from the B-decay system, and to elucidate the origin of CP violation.

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